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Automatic Calibration Of Control Parameters Based On Merit Function Spectral Analysis

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Abstract

The number of actuations influencing the combustion is increasing, and, as a consequence, the calibration of control parameters is becoming challenging. One of the most effective factors influencing performance and efficiency is the combustion phasing: for gasoline engines control variables such as Spark Advance (SA), Air-to-Fuel Ratio (AFR), Variable Valve Timing (VVT), Exhaust Gas Recirculation (EGR) are mostly used to set the combustion phasing.
The optimal control setting can be chosen according to a cost function, taking into account performance indicators, such as Indicated Mean Effective Pressure (IMEP), Brake Specific Fuel Consumption (BSFC), pollutant emissions, or other indexes inherent to reliability issues, such as exhaust gas temperature, or knock intensity.
The paper proposes the use of the extremum seeking approach during the calibration process. The main idea consists in changing the values of each control parameter at the same time, identifying its effect on the monitored cost function, allowing to shift automatically the control setting towards the optimum solution throughout the calibration procedure. Obviously, the nodal point is to establish how the various control parameters affect the monitored cost function and to determine the direction of the required variation, in order to approach the optimum. This task is carried out by means of a spectral analysis of the cost function: each control variable is varied according to a sine wave, thus its effect on the cost function can be determined by evaluating the amplitude of the Fast Fourier Transform (FFT) of the cost function, for the given excitation frequency. The FFT amplitude is representative of the cost function sensitivity to the control variable variations, while the phase can be used to assess the direction of the variation that must be applied to the control settings in order to approach the optimum configuration. Each control parameter is excited with a different frequency, thus it is possible to recognize the effect of a single parameter by analyzing the spectrum of the cost function for the given excitation frequency.
The methodology has been applied to data referring to a PFI engine, trying to maximize IMEP, while limiting the knock intensity and exhaust gas temperature, using SA and AFR as control variables. The approach proved to be efficient in reaching the optimum control setting, showing that the optimal setting can be achieved rapidly and consistently.

keywords: calibration; SA, AFR, cylinder pressure

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1. Introduction

Spark Ignition engines performance are influenced by combustion phasing and duration: these parameters are affected by control settings, such as Spark Advance, Air-Fuel Ratio, Exhaust Gas Recirculation, Variable Valve Timing, etc. Engine Electronic Control Units (ECU) usually select the proper control parameters setting from lookup tables or grey box models, adapting to the engine state [1]. A calibration procedure is therefore required, to determine the values that will be used by the ECU during engine operation. The process is usually carried out on the test bench, keeping the engine in steady conditions for many engine cycles (sometimes thousands), to filter out the effect of stochastic phenomena (cycle-to-cycle variation, knock).

The calibration process benefits of detailed information on the combustion characteristics, that can be gathered by means of in-cylinder pressure sensors: the target function is often defined on the base of combustion parameters.

Combustion parameters could be estimated based on the analysis of other signals [2-9], but usually for calibration purposes cylinder pressure is favored, due to better performance. The use of other signals could be of interest for on-board applications of the proposed calibration methodology: the Engine Control Unit could perform a continuous combustion calibration.

When the number of control parameters influencing the cost (or merit) function increases, DOE techniques are often considered the only solution ([10, 11]). Many examples can be found in the literature, based on the evolution of the described concepts: Halliday et al. (in [12]) and Rose et al. (in [13]) show how two-stage techniques can be successfully applied in engine mapping operations. This approach catches the different nature of the experiment factors (throttle opening, engine speed, SA) on the optimization output (engine torque), but the methodology is entirely based on a black-box model, requiring many steady state tests, especially when complex phenomena are condensed in few simple mathematical relationships. A possible solution is to use more complex mathematical regressions, as shown in [14], where radial basis functions are proposed instead of polynomial models. Suzuki et al. in [15] propose a different way, using model-based methodologies for the calibration process, employing both cycle simulation and regression analysis. The model-based approach improves the robustness, but still the methodology requires many steady state tests.

Other authors approach the problem of SA calibration (for Maximum Brake Torque, MBT) from a different point of view, defining a combustion invariant able to represent the optimal combustion phasing condition. Eriksson in [16] shows that an appropriate parameter is the MFB45, while Haskara et al. in [17] leans toward the maximum mass fraction acceleration. These methodologies tend to fail in particular running conditions, such as low loads, high Exhaust Gas Recirculation, etc. Besides, it has been shown [18, 19] that it is not necessary to set a well-defined value for the optimal combustion phasing throughout the entire engine operating range, simply because the optimal condition can be easily determined during engine operation.

In [20] Patterson proposes a methodology aimed at setting the optimal SA during engine speed sweeps (with constant throttle position). A target combustion phase is assigned, and SA is changed sweep after sweep, driving the cylinders combustion phasing towards the target. The drawback of this technique consists in the definition of the target combustion phase, its value being influenced by operating conditions.

This paper will show how combustion information can be used for a real-time optimization of control parameters, based on a totally different concept: the control parameters are changed simultaneously, with sinusoidal variations carried out at different frequencies. The signature of a given control parameter on the target function can be highlighted by evaluating the amplitude of its variation at the excitation frequency. This approach, known as extremum seeking, has been introduced in the 1920s and since then has been used to solve optimization problems of different types [21]: since the approach is not based on a model, it has been used in different engineering areas, from the tuning of gas turbine combustion controllers [22, 23], to objects recognition in robot applications [24], from damping instabilities in hydraulic machines [25] to internal combustion engine combustion control [26-29]. Haskara et al. in [26] show how EGR and SA control can be coordinated, using the ion current signal to pursue the maximum allowable dilution, while adapting the SA to the given EGR rate by means of an extremum seeking controller (ESC). Krstic et al. in [27, 28] use the ES control to manage SA and tune the PID (Proportional Integer Derivative) controller gains of a thermal management system controlling the combustion phase of an HCCI engine. Lee et al. in [29] show how the ESC can be used in transient conditions to control SA in Flex-Fuel applications.

In this paper the Extremum Seeking methodology is used for calibration purposes, solving a typical MIMO (Multi-Input Multi-Output) calibration problem: the definition of SA and AFR values maximizing the IMEP while limiting knock intensity and exhaust temperatures. Since in the area of engine controls many of the inputs and outputs of the system may only change on a cycle basis, the extremum seeking approach is applied exciting the inputs and analyzing the outputs at fixed cycle frequencies, i.e., excitation frequencies will change with engine speed.

The ESC methodology is used with an original approach, allowing a clear identification of the control parameters impact on the target function, a fast response and low computational power requirements. A spectral analysis of the target function is used to establish how the input control parameters affect the outputs of the controlled system. Each control variable is altered according to a sine wave, thus its effect on the system outputs can be highlighted via the Fast Fourier Transform (FFT) of the target function. The FFT amplitude corresponding to the excitation frequency is representative of the target function sensitivity to the control variable, while the phase can be used to assess the direction of the variation that must be applied to the control settings in order to approach the optimum configuration. Each control parameter is excited with a different frequency, thus it is possible to recognize the effect of the single control parameter by analyzing the spectrum of the target function for the given excitation frequency.

Nomenclature

f	Target function (time domain)
F	Target function (time domain)
k	slope factor for exhaust temperature target function component
k_c	ESC gain
j	imaginary unit
m	frequency component of the FFT
m_c	component corresponding to the control parameter modulation frequency
N	Number of samples for the FFT evaluation
T_{exh}	Exhaust temperature
T_{th}	Exhaust temperature
Δc	Control setting (SA, AFR) variation
Φ	FFT phase component

1.1. Experimental setup

The ESC calibration approach has been developed based on experimental data referring to a 4-cylinder 1.2 liters automotive SI (Spark Ignition) engine.

Engine speed was controlled by the eddy-current brake controller; a motor driving the throttle was feedback controlled to set engine load. Intake manifold temperature, Air to Fuel Ratio, coolant and oil temperatures have been maintained constant during the tests.

In-cylinder pressure was measured by means of Kistler 6117BCD15 measuring spark plugs and 5064B21 charge amplifiers. Angular position tracking has been carried out by means of a Sensor Instrument FIA-F optical sensor, coupled to a crankshaft-mounted measurement disk with 120 markers per revolution. The in-cylinder pressure signals have been sampled @ 100kHz, while the angular reference signal (encoder) has been detected by means of a timer-counter digital channel, with a 10 MHz clock. All the signals have been sampled using a National Instruments cRIO System.

The in-cylinder pressure signals have been low-pass filtered by means of an anti-aliasing analog filter set @ 20 kHz: the filter delay has been compensated in order to avoid referencing errors. A 3 kHz zero-delay low-pass 4th order Butterworth digital filter has been used for IMEP and net Cumulative Heat Release calculations, in order to eliminate the combustion chamber resonance effect.

The calibration methodology has been tested in real time on the motorcycle unit. In-cylinder pressure signals are sampled, filtered, placed on the angular domain and used for the cycle-by-cycle indicating analysis, thanks to the FPGA (Field Programmable Gate Array) hardware [30].

2. Extremum seeking controller

Extremum seeking control is essentially a methodology to maximize (or minimize) the outputs of a process, by setting proper inputs. The methodology is not based on a model, so the optimal output is not previously estimated: the controller drives the inputs to optimize the outputs in real-time, choosing the direction and amplitude of control parameters variations, based on experience of the plant response to the input control law.

The ways the controller gains experience on the plant sensitivity to control parameters can be different: one of the most common approach is to determine the slope of the input-output relationship, and then driving the slope to zero. To obtain the slope, sinusoidal perturbations with a given frequency are applied to the control input, while monitoring the output. The effect of the input parameter on the output is usually highlighted by means of a modulation of the input signal and a demodulation of the output.

In the typical ESC scheme, the plant input (c) is determined by adding to the estimated optimal control setting ($\hat{c}$) a sinusoidal perturbation (modulation).

The plant output (the target function f) is then high-pass filtered, to exclude low-frequency noise, and multiplied by a sine function (demodulation) of the same frequency of the perturbation added to the input. The product of the high-pass filtered output and the sine wave are then low-pass filtered, to exclude high frequency effects: this operation gives as an output the optimal control setting estimate ($\hat{c}$).

In this paper, instead of using modulation and demodulation, the plant sensitivity to perturbations is detected following an original approach: since the given control parameter is modulated with a fixed frequency, its signature on the plant output can be found at the same frequency. The target function spectrum is then analyzed for the frequencies excited by the control parameters modulation, to gain information on the slope relating input and output.

The target function sensitivity to a given control parameter is evaluated as the ratio between its FFT amplitude corresponding to the excitation frequency, and the target function average value. The higher the sensitivity, the higher the correction that must be applied to the previous control parameter optimal value estimate. The optimal setting will be attained as the target function has reached a maximum or a minimum, i.e., as the plant will show no sensitivity to the control parameter variations.

As regards the sign of the correction, it can be determined based on the FFT phase corresponding to the modulation frequency: if the output target function has the same phase of the excitation input, then increasing the control parameter values will lead to increase the target function value; on the contrary, if phases have opposite signs, it means that an increase in the control parameter causes a decrease in the target function. These considerations can be used to determine the sign of the correction to the estimated optimal control setting, in order to minimize (or maximize) the target function.

2.1. Controller Structure

The methodology described in the previous section has been applied to a calibration problem consisting in the determination of optimal SA and AFR values, taking into account IMEP, and exhaust temperature for the definition of the target function, while limiting the SA to the knock-free region.

This problem is often faced in turbocharged gasoline engines calibration, where in high-speed/high-load conditions, SA must be retarded due to knock, causing high exhaust temperatures, that are then reduced by means of rich AFR values. For the engines under analysis the constraints on exhaust temperatures or knock may not be as limiting, but the focus of the work is the setup of the calibration methodology.

Exhaust temperature should affect the target function value only when it exceeds a given threshold, while IMEP should drive the target function directly. The target function is then defined as:

$$f = IMEP \cdot \left(1 - \frac{1}{1+\alpha e^{k\cdot(T_{th}-T_{exh})}}\right) \tag{1}$$

According to the definition of the target function given in equation (1), when exhaust temperature reaches the threshold level, the temperature component of the target function reaches the value $\alpha/(1+\alpha)$.

The slope factor k allows modulating the temperature factor roll-off as a function of exhaust temperature. The plant response to AFR variations is slower than to SA variations, thus SA modulation frequency and amplitude have been fixed to 20 engine cycles and 4 degrees, while 100 engine cycles and 0.5 AFR were used for AFR modulation.

Once the modulation has been activated, the Fast Fourier Transform (FFT) of the target function f is evaluated: the minimum observation window for the FFT operation should be the modulation period. In this way the excitation frequency of the control parameter would be equal to the first harmonic component of the base-frequency (corresponding to the observation period). The evaluation of amplitude and phase of the first harmonic of the target function spectrum is sufficient to evaluate its sensitivity to the considered control parameter. Obviously, the operation could be carried out on the larger time-base, i.e., on the period corresponding to the slower control parameter (in the present case, AFR): if the spectrum of f is evaluated every 100 engine cycles, the first harmonic is representative of the target function sensitivity to AFR, the fifth harmonic emphasizes the effect of SA modulation.

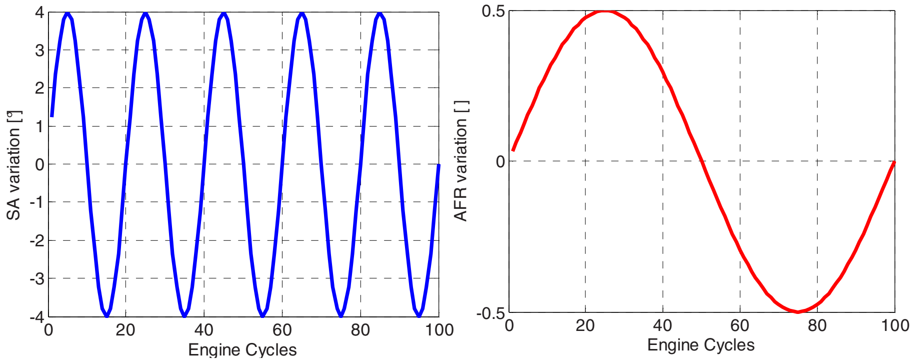

Fig. 1. (a) SA modulation; (b) AFR modulation.

Figure 1 shows an example of how SA (a) and AFR (b) are excited in order to assess the control parameters effect on the merit function. The system responds to the excitation with IMEP and Texh variations that will change the merit function values, according to equation (1): two frequencies should be observed in the merit function spectrum, in order to evaluate the effects of the control variables. Since SA and AFR variations periods are defined in terms of engine cycles (20 and 100 respectively), the two frequencies will be fractions of the engine cycle frequency (1/20 and 1/100 respectively for SA and AFR).

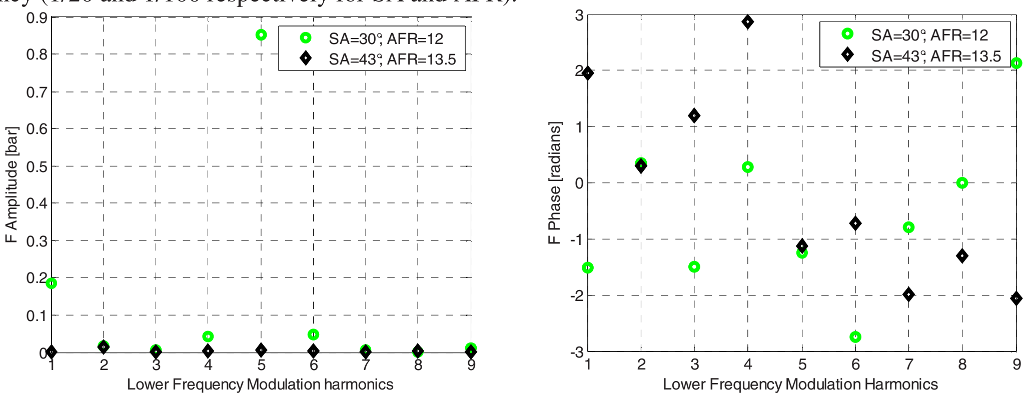

Fig. 2. (a) SA modulation; (b) AFR modulation.

Figure 2 shows how the target function f responds to control setting the variations: the merit function has been sampled over a period of 100 engine cycles, thus the first frequency component in the spectrum pertains to AFR variation, while the fifth component (corresponding to a period of 20 engine cycles) refers to SA variations. The spectrum amplitudes are representative of the plant sensitivity to the control parameters variations, and can be used to define a new control setting. When the optimal setting is reached, the amplitudes tend to zero, and the phases signs will start fluctuating (this typical behavior will be further discussed in the followings). Thus, the amplitudes can be considered as measure of SA and AFR variations to apply, in order to approach the optimal setting. The direction of the variation is determined by comparing the phase of the modulated control parameters to that of the target function for those harmonics corresponding to the excitation (first and fifth harmonics in this example): Figure 2(a) shows that at the beginning of the optimization process (SA=30°, AFR=12) the amplitudes are high, both for the first and the fifth cycle harmonics, and both phases have negative values. AFR and SA modulation phases, represented in figure 2(b) have negative values, too, meaning that increases in SA and AFR will lead to increases in f. At the end of the calibration process (SA=43°, AFR=13.5) SA and AFR have been optimized, leading to very low amplitudes. As regards the phases, their sign fluctuates, leading to small corrections of opposite signs.

Only the frequencies pertaining to the control parameters variations have to be evaluated. Usually, the FFT is evaluated as:

$$F(m) = \sum_{n=1}^{N} f_n \cdot e^{\left(-j\cdot 2\cdot\pi\cdot(m-1)\cdot\frac{(n-1)}{N}\right)} \qquad (2),$$

m being the index of the considered harmonic ($1 \le m \le N$).

The evaluation in this case should be performed only for m=1 and m=5, requiring modest computational power: this type of operation, carried out every 100 cycles, is compatible with real-time hardware (it may also be compatible with actual ECUs).

Once the FFT (amplitude and phase) has been evaluated for the given harmonic component, a correction of the control parameter, drifting its value towards the optimum, is computed as

$$\Delta c = k_c \cdot \frac{|F(m_c)|}{\frac{1}{N}\cdot\sum_{n=1}^{N} fn} \cdot sgn\left(\frac{\Phi(m_c)}{\Phi(c)}\right) \qquad (3)$$

Equation 3 shows how the correction of the control parameter is evaluated taking into account the relative variation of the target function: the FFT amplitude is normalized with respect to the mean value of f, in order to avoid load-dependent gain scheduling (f is proportional to IMEP). As regards the sign of the correction, it is evaluated as the sign of the ratio between the phases of the target function harmonic and the control variable modulation.

In order to avoid excessive knock intensity during the calibration, a statistical knock index first introduced by Leppard [31] and modified according to the observation of Naber et al. [32], was used: the Maximum Amplitude of Pressure Oscillations (MAPO), a commonly used knock index [33], is statistically analyzed, allowing to determine the knock intensity level of the given running condition. In order to reduce the number of engine cycles necessary for the statistical analysis, the MAPO distribution is fitted by means of a log-normal probability density function (pdf). The analysis can lead to determine the level of MAPO corresponding to a given percentile of engine cycles, or the percentage of knocking cycles exceeding a given threshold, as explained in [34]: the fitting allows giving reliable results even using a statistical basis of 100 cycles.

Once the percentage of knocking cycles becomes unacceptable, SA is saturated, preventing the calibration algorithm to persist in searching the optimal control setting in a knocking area. Since the value of SA leading to knock depends on the AFR value, a selective saturation is applied, taking into account the actual AFR: the SA causing the percentage of knocking cycles to reach the limit will not be exceeded only for values of AFR lower or equal to the actual.

3. Engine Response Simulation

In order to develop the calibration methodology, a simulation of the engine response to SA and AFR has been setup. The simulation relies on combustion data referring to the considered engine. To give the proper feedback to the controller, the model must be able to simulate the response to SA and AFR in terms of IMEP and exhaust temperature, but also cycle-to-cycle variations, and knock tendency.

Figure 3 shows how the simulation is organized, for a given operating condition (speed, load): the structure, partly based on LookUp Tables (LUT) and partly on block reconstructing the dynamics, is similar for the generation of the three output parameters (Texh, IMEP, MAPO). The generation is carried out cycle-by-cycle, catching the engine static and dynamic behavior.

Exhaust temperatures are not simulated on a cycle basis, since the sensor dynamics is usually too slow to allow cycle-based measurements. The generation of exhaust temperature is therefore based on a LUT, catching the temperature dependence on AFR and SA, followed by a first order dynamics block, representing the sensor dynamics.

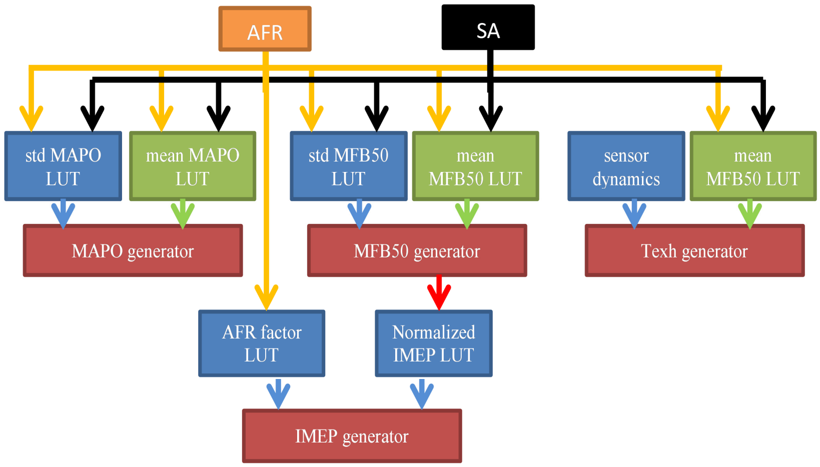

Fig. 3. Engine response simulation

To generate reliable IMEP values, a statistical representation of the combustion phenomenon has been setup: as remarked in [35-37], cycle-to-cycle variation affects the early stages of the combustion, spreading its effect through the entire process. The phenomenon can be well represented by means of a combustion phase variation, distributed according to a normal pdf. The mean value of MFB50 is influenced by both SA and AFR settings, while the standard deviation is mainly influenced by AFR. Once the distribution is generated, the value of MFB50 is available on a cycle basis. The combustion phase determines the efficiency, i.e., the ratio between the IMEP that will be achieved with the given MFB50, and the maximum achievable in the present running condition, which depends on AFR. Both the normalized IMEP as a function of MFB50 and the value of maximum achievable IMEP as a function of AFR are stored in LUTs.

Finally, MAPO is generated following the same approach: the mean value and standard deviation of the knock index are generated by means of LUTs, using AFR and SA as inputs. The given cycle MAPO value is then generated according to a log-normal probability density function.

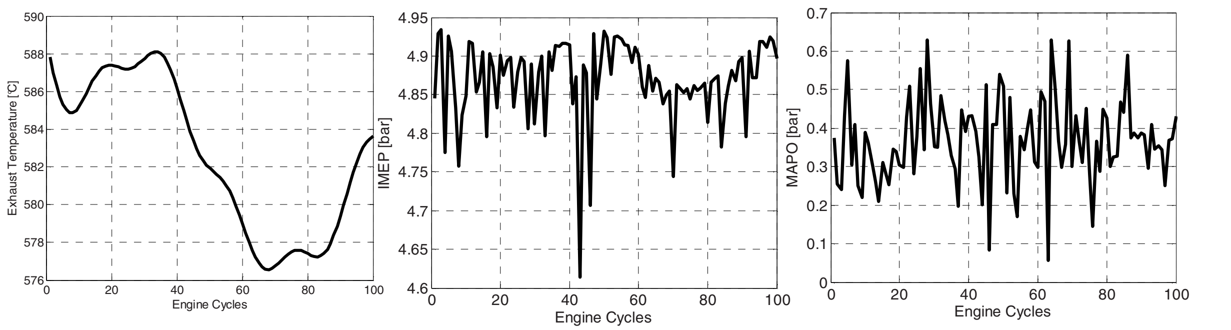

Fig. 4. Engine simulation results (a) Exhaust temperature; (b) IMEP; (c) MAPO

Figure 4 shows how output parameters are generated during a test where SA and AFR are varied according to figure 1: the effect of SA and AFR modulation is visible in the exhaust temperature trend, while both IMEP and MAPO show the effect of cycle-to-cycle variation.

4. Controller Simulation

The combustion model described in the previous section has been used to test the extremum seeking controller and calibrate its parameters: the algorithm has been run in several different operating conditions, varying setup constants, such as the gains (kc in equation 3) and AFR and SA amplitude and frequency. The algorithm has been optimized to achieve promptness and precision: on one hand the number of engine cycles to reach the optimal control setting should be as low as possible, on the other hand the setting should keep constant after the convergence to the optimal solution.

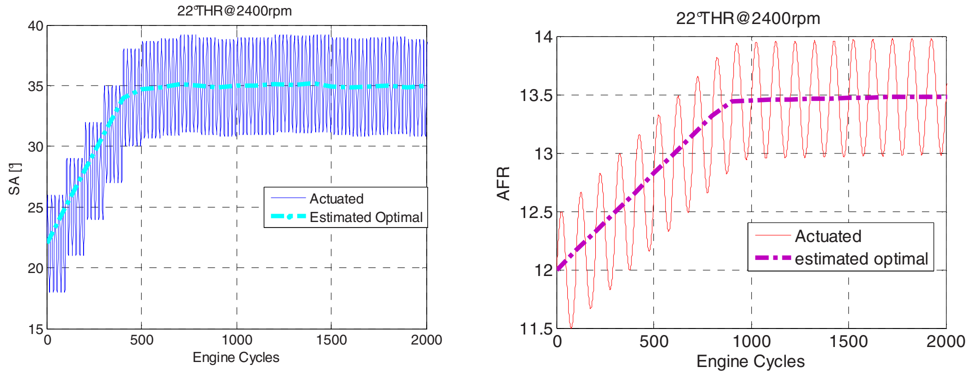

Fig. 5. (a) extremum seeking control of SA; (b) extremum seeking control of AFR

Figure 5 shows the result of a simulation where the controller changes the values of SA (a) and AFR (b) at the same time: it can be noticed that the optimal SA (35°) is reached and maintained in the range ±0.5° after 500 engine cycles (25 seconds), starting from an optimal estimate of 20°. As regards the optimal AFR (13.5) setting, it is reached and maintained in the range ±0.05 AFR in around 1000 cycles, starting from a first estimate of AFR=12.

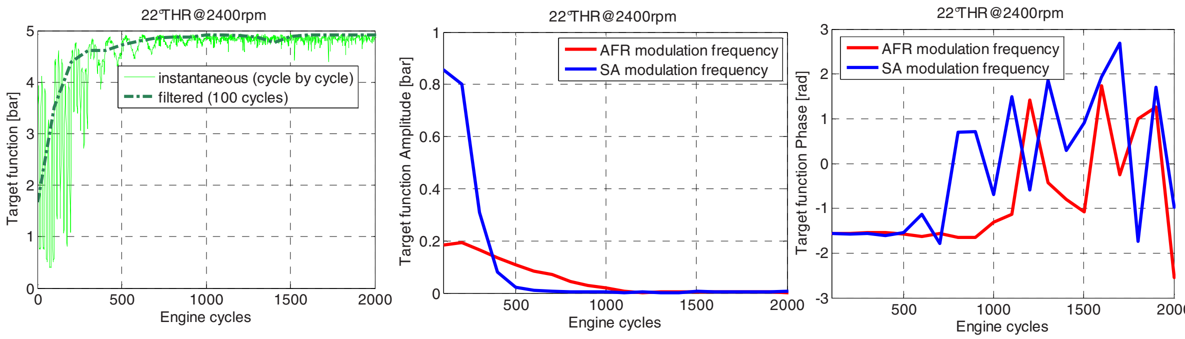

Fig. 6. (a) target function variation; (b) target function amplitudes for SA and AFR modulation frequencies; (b) target function phases for SA and AFR modulation frequencies

Figure 6 (a) shows how the ESC increases the target function value, using its amplitude and phase evaluated at SA and AFR modulation frequencies: as it can be seen, at the beginning the amplitudes (Fig 6b) are high both for AFR and SA, while phases (Fig 6c) are both negative (concordant with modulation phase), meaning that SA and AFR must be increased, as shown in Figure 5. It can be noticed that after 500 engine cycles the amplitude at SA modulation frequency reaches very small values, while after 800 cycles the phase sign changes and starts oscillating. The same happens for amplitude and phase at AFR modulation frequency, after 1000-1200 cycles. This behavior is very similar to that observed in [38] for the evolution of the AFR signal phase as the action of the AFR balancing controller becomes effective. Once again, the cause can be ascribed to the decreasing in the Signal-to-Noise Ratio (SNR) as the optimal configuration is approached.

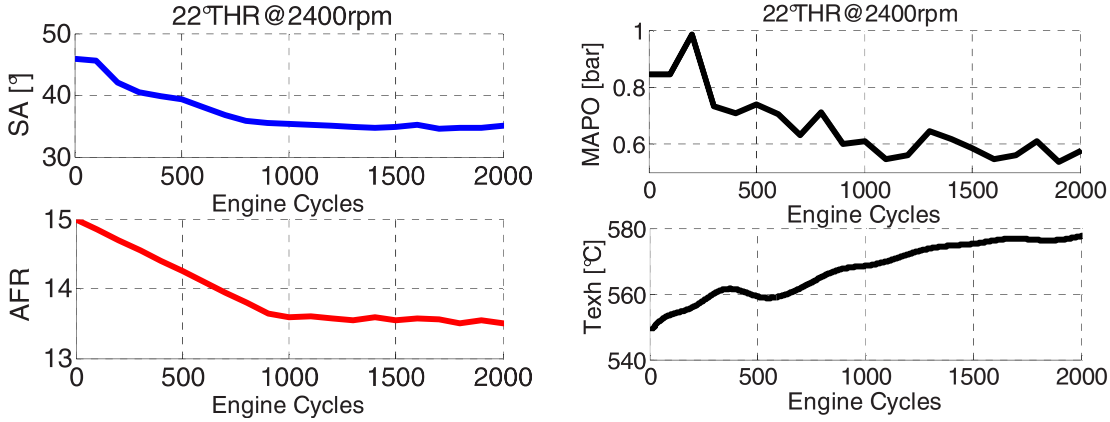

Fig. 7. (a) AFR and SA optimization results; (b) Exhaust temperature and MAPO during the optimization

Figure 7 shows an optimization example carried out starting from AFR and SA values higher than the optimal setting: the convergence (Fig 7a) is slightly slower than in the previous example, especially referring to SA. This is partly due to the lower sensitivity of IMEP to SA for lean lambda values, and partly to higher SA required by leaner AFR. The abrupt decrease in SA at the beginning of the test is related to knocking combustion: the statistical knock index exceeds the threshold, requiring a combustion retard (Fig 7b).

5. Conclusions

The paper presents an original approach to multi-variable calibration, based on Extremum Seeking Control. The ESC algorithm has been modified, simplifying the identification of the calibration parameters influence on the plant behavior, based on the use of Fast Fourier Transform. This approach allows a precise identification of the inputs (control parameters) effect on the outputs (target function), and a low computational cost.

The calibration methodology has been first setup in a simulation environment: the combustion model, although based on lookup tables extracted from experimental data, is able to reproduce cycle-to-cycle variations and knock intensity, by means of statistical observations of the engine behavior. The ESC has been developed off-line to optimize AFR and SA, defining the target function based on IMEP and Texh, while limiting knock. The controller drives SA and AFR to the optimal setting in less than 1000 engine cycles, and it can be easily implemented in real-time, coupled to combustion analysis systems, in order to perform real-time combustion control or calibration.

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